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Title: Dynamic Measurement and Mathematical Modeling of the Temperature History on Hot Dog Surfaces During Vacuum-Steam-Vacuum Processes

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Dynamic measurement and mathematical modeling of the temperature history on hot dog surfaces during vacuum–steam–vacuum processes ☆

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Abstract

The objective of this study was to develop an instrumentation system to measure the surface temperature of hot dogs during VSV processes. Results indicated that the pressure in the treatment chamber responded immediately and accurately to the events of VSV. The surface temperature history, however, followed an exponential trend after saturated steam was flushed into the treatment chamber. A mathematical model was developed to simulate the surface temperature history during steam pasteurization processes. According to the model, a 5-log reduction in *L. innocua* inoculated onto the surface of hot dogs could be achieved using 110 °C steam for 0.1 s, provided that the surface was perfectly smooth and bacteria were all distributed on the surface. However, bacteria still survived the VSV treatment even when higher temperatures were used. The incomplete destruction of bacteria on hot dog surfaces using current VSV processes may be due to the fact that the pores are filled with water and heat must penetrate into a certain depth under the surface of hot dogs in order to eliminate *L. monocytogenes*. This study suggested using a single long steam treatment cycle, instead of multiple short VSV cycles, for a complete destruction of bacteria hidden beneath the surface of ready-to-eat solid foods.

Keywords: Surface pasteurization; Hot dogs; Modeling

1. Introduction

Vacuum–steam–vacuum (VSV) is a surface pasteurization technology recently developed by Morgan (1994) and Goldberg, Radewonuk, Kozempel, and Morgan (2001). This technology was developed to rapidly treat the surfaces of solid foods using ultra-high temperature saturated steam without causing thermal damage. The fundamental principle behind the development of the VSV technology is that the thermal energy required to cause damage to food surfaces, such as protein denaturation, is much higher than that needed to kill bacteria. This technology was originally developed to treat highly heat-sensitive solid foods, such as raw meats of chicken. It is considered as a gentle pasteurization process for killing foodborne pathogens on food surfaces.

In the patent filed by Morgan (1994), the author examined many physical and chemical surface pasteurization technologies and discovered that the available technologies could not effectively kill bacteria hiding in the pores, irregularities and other imperfections on the surface of meat. To treat the bacteria hiding in these areas, Morgan (1994) developed the VSV process. It

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involved four successive steps of vacuum and steam to achieve bacterial destruction on the surfaces of meat enclosed in an airtight treatment chamber. In the first step, vacuum was applied to evacuate air from the treatment chamber. The air and moisture surrounding the meat sample was further removed by flushing the chamber with a stream of low temperature steam. Evacuating the air and moisture surrounding the meat sample, according to Morgan, Radewonuk, and Scullen (1996a, 1996b), enabled high temperature saturated steam to stream into the pores, irregularities and other imperfections on the surface. Therefore in the third step the process continued with flushing high temperature saturated steam into the treatment chamber. The thermal energy released from the ultra-high temperature steam would almost instantaneously kill the bacteria. In the final step vacuum was applied again to remove the steam from the treatment chamber. The vacuum also caused evaporation of the steam condensate back to the treatment chamber, thus reducing the surface temperature of the meat sample. All four steps formed a treatment cycle. The process could be repeated with multiple treatment cycles to achieve a desirable bacterial kill.

In the studies reported by Morgan et al. (1996a, 1996b) using a prototype VSV device, the authors inoculated the surfaces of small fresh chicken, beef, and pork samples (~5 g) with *Listeria innocua* (10^7) and then subjected them to various steam temperatures (121–157 °C) and exposure times (26–103 ms). The bacterial kills consistently ranged from 1.9 to 4.0 logs. The highest bacterial kills were observed in chicken meats with 138 °C for 26 ms and 121 °C for 48 ms. Increasing the steam temperature or the treatment time did not seem to improve the bacterial kill. For example, 2.7–2.8-log reductions were achieved in chicken at both 149 and 157 °C for 26 ms.

A scaled-up VSV apparatus, capable of treating whole chickens, was later developed (Goldberg et al., 2001). Kozempel, Goldberg, Radewonuk, and Scullen (2000a) used the apparatus to treat Cornish hen, Cornish hen cut in half, fryers cut in half, and chicken drumsticks with an objective to see if the VSV process was effective in killing naturally occurring microorganisms. A range of steam temperatures (116–157 °C) was used. The steam treatment time was up to 0.1 s. Experimental results showed the VSV process could only achieve 0.5–1.0 log reduction for the naturally occurring *E. coli*, coliforms, and APC. Kozempel, Goldberg, Radewonuk, and Scullen (2001a) conducted another study to treat whole chickens using the VSV apparatus modified with a mandrel inside the treatment chamber to inject steam directly into the visceral cavity of chicken carcasses. Whole chickens inoculated with *L. innocua* at the level of 4.5 log (CFU/ml) were treated in the modified VSV apparatus under an optimum condition (0.1 s initial vacuum, 0.1 s steam at 138 °C, and 0.5 s final vacuum). Experimental results showed that bacterial kill was 0.7–0.8 log (CFU/ml). With deboned chicken breast meats, the bacterial kill was 1–1.3 log (CFU/ml). Similar results were observed in the treatment of catfish using cycles of vacuum and steam (Kozempel, Marshall, Radewonuk, Scullen, & Bal'a, 2001b). Depending on the number of treatment cycles (1–3) and steam temperature (138 or 143 °C), the observed bacterial kills ranged from 0.7 to 2.1 logs. Sommers, Kozempel, Fan, and Radewonuk (2002) investigated the combined effect of VSV and ionizing irradiation on inactivation of *L. innocua* inoculated on ham. They discovered that two cycles of VSV treatment (138 °C for 0.1 s for each cycle) achieved 1.69-log reductions on ham meat and 2.35-log reductions on ham skin.

The VSV process was more successful for hot dogs and some fruits and vegetables. Kozempel, Gildberg, Radewonuk, Scullen, and Carig (2000b) reported that treating hot dogs surface-inoculated with *L. innocua* (~10^6) using 138 °C saturated steam (0.3 s in each cycle) for 2–4 cycles could achieve more than 4 logs of bacterial destruction. However, 0.65–2 logs of *L. innocua* still survived. In treating selected fruits and vegetables, similar amount of bacterial survival was also observed (Kozempel, Radewonuk, Scullen, & Goldberg, 2002).

It is fairly difficult to explain the fact that bacteria could survive the severe heating conditions at temperatures above 116 °C and that increasing the steam temperature or the steam treatment time did not lead to improved bacterial kill. One possibility is that the surface temperature of the foods treated in the VSV chamber might have never been raised to a condition that could kill the bacteria completely. Since none of the previously conducted studies measured the surface temperature of the foods, one could not preclude this possibility. It was therefore the main objective of this study to develop an instrumentation system that could dynamically measure the surface temperature of foods during VSV processes.

2. Materials and methods

2.1. Samples

Frozen hot dogs (beef) were purchased from a local manufacturer. Each hot dog was 2.2 cm in diameter and 13.3 cm in length. The hot dogs were manufactured in the same batch without adding any antimicrobial agents, and were packaged in one-pound (0.454 kg) vacuum packages. Upon receiving, hot dogs were kept frozen (~−20 °C) in a freezer until ready for use in experiments. Frozen hot dogs were thawed overnight in a refrigerator (~4 °C) prior to experiments.

2.2. Ultra-fine thermocouples for surface temperature measurement

The VSV processes were operated at very high speeds. The steam exposure time was in the scale of a few milliseconds in a cycle after high temperature steam was injected to the treatment chamber. Most temperature sensors on the market could not respond fast enough for the VSV process. To measure the surface temperature of foods, ultra-fine (52 AWG) thermocouple wires (Type-T) were custom-ordered from California Fine Wire Co. (Grover Beach, CA). Each strand of the thermocouple wires was 0.00078 in (or 1.98×10^{-3} cm) in diameter, and was superficially coated with a thin layer of heavy polyurethane/nylon for electric insulation. Each pair of thermocouples was welded in a thermocouple welder (Model 116SRL, B.J. Wolfe Enterprises, Inc., Agoura Hills, CA), which was capable of welding metal wires with sizes ranging from 55 to 20 AGW. Each pair of thermocouples was tested for electrical conductivity and total resistance before being used to measure surface temperatures during VSV processes.

2.3. Pressure sensor

To measure the pressure response in the treatment chamber during a VSV process, a pressure sensor (Model AF-A1-G-V2-N1, DJ Instruments, Billerica, MA) was used. This pressure sensor was capable of measuring pressures ranging from vacuum to 5.0 bar (gauge). The response time of the pressure sensor was less than 1 ms according to the manufacturer. The pressure sensor was factory-calibrated and ready for use when delivered.

2.4. Instrumentation

To measure temperature, a 12-bit high-speed thermocouple data acquisition board (ADAC 5508TC, American Data Acquisition Corp., Woburn, MA) was used. This board had 8 A/D channels and could be directly inserted into an ISA bus of a personal computer. The total hardware conversion time was 85 μs, with a maximum acquisition rate of 8 kHz.

To measure the signal from the pressure sensor, another high-speed A/D converter (PCI-DAS1200, Measurement Computing Corp., Middleboro, MA) was used. This was a 12-bit, 8-channel PCI board, with a minimum data throughput of 300 kHz.

2.5. Response time of thermocouples

Two thermocouples (50–60 cm) were prepared to measure the time constant of the temperature sensors. Each tip of thermocouple wires, equilibrated to room temperatures, was instantaneously submerged into a circulating water bath (PloyStat EW-12105-20, Cole-Parmer, Vernon Hills, Illinois) maintained at a constant temperature (37 °C), which was approximately 12 °C above room temperatures.

One thermocouple was tested at a time. Raw voltage signals from the thermocouple were fed to the ADAC 5508TC board and were recorded by Lab View 6.0 (National Instruments Corp., Austin, TX) at a sampling rate of 8 kHz. Data acquisition was initiated before the sensor was dropped into the water bath. A total of 40,000 data in each test, equivalent to 5 s of measurement time, were collected. Three replicates of measurement were conducted to obtain the average response time of each sensor.

The response time or time constant (τ) of a thermocouple is usually defined as the time required to reach 63.2% of a step change in temperature under a specified set of conditions (Bebedict, 1977). Mathematically, the response time of a thermocouple can be defined by

$$\frac{T_e - T}{T_e - T_0} = e^{-t/\tau} \tag{1}$$

In Eq. (1), T is the real-time temperature, T_0 is the initial (or ambient) temperature, T_e is the water bath temperature (°C), t is the time, and τ is the sensor response time. Since the raw voltage data signals from a thermocouple were continuously collected, Eq. (1) can be modified to:

$$\begin{aligned} v &= v_0 \quad t < t_1 \\ v &= v_e - (v_e - v_0)e^{-\frac{t-t_1}{\tau}} \quad t \geqslant t_1 \end{aligned} \tag{2}$$

In Eq. (2), v_0 is the voltage signal corresponding to the ambient temperature, v_e is the voltage signal corresponding to the water bath temperature, t_1 is the time when the thermocouple was subject to a step change in temperature. Since Eq. (2) was not linear, a nonlinear regression procedure in a statistical package—NCSS 2000 (Hintze, 1999) was used to obtain τ for each sensor.

2.6. Calibration of thermocouples

Since the thermocouple wires were custom-ordered and might not be made from standard materials, their accuracy for temperature measurement must be determined. Four thermocouples were prepared for temperature calibration. During calibration, all four thermocouples were simultaneously placed in a circulating water bath (Model PloyStat EW-12105-20, Cole-Parmer Co., Vernon Hills, Illinois) maintained at 10, 20, 30, 40, 50, 60, 70, 80, 98, 110, 120, 130, and 145 °C. At temperatures below 100 °C, water was used as a heating medium. At temperatures above 100 °C, silicone oil (viscosity = 350 cst) was used as a heating medium. At each temperature set point, the water/oil bath temperature was calibrated against a NIST-traceable mercury thermometer. After equilibrium, the temperature signals from each sensor were recorded at a 5 s

interval for 120 s. The average of all 25 data points from each sensor was used to represent the temperature reading measured by the thermocouple.

2.7. VSV apparatus

The pilot-scale VSV apparatus used by Kozempel et al. (2000b) was used with a modified chamber. The original chamber was disconnected from the apparatus. A new VSV chamber, specially designed for treating hot dog samples, was fabricated and installed (Fig. 1). The new chamber was made from a stainless pipe, which was 4.13 cm in internal diameter, 4.45 cm in external diameter, and 30.48 cm in length. One end of the chamber was connected to a 3-way valve. The other end of the chamber was used for sample loading. Only one hot dog could be loaded into the VSV chamber at each time. A stainless steel probe, modified from a standard thermocouple probe, was used to hold a sample in the VSV chamber. The probe was 0.3175 cm in diameter and 18 cm in length, with one end fixed to the cap of the VSV chamber. Depending on the position of the 3-way valve, the chamber could be either open to steam, vacuum, or atmosphere. The 3-way valve was driven by a servo motor with its position precisely monitored by an optical disk encoder. The pressure sensor was connected to a port in the middle of the VSV chamber. To prevent any loss of the steam energy, the VSV chamber was wrapped around with electric heating elements. A layer (~3.8 cm) of insulation foam was used to cover over the electric elements. The temperature of the heating elements was set to the temperature of the steam tank. Except for loading and unloading samples, the VSV apparatus was operated by a computer-based control system.

2.8. VSV operation

A thawed hot dog sample was mounted to the sample holder. The probe of the sample holder was inserted along the centerline and was approximately 3/4 into the hot dog sample. After the sample port was manually closed, the 3-way valve was programmed to complete a sequence of operations. It was first switched to the vacuum position to evacuate air from the VSV chamber, then to the steam position to flush steam into the chamber, and then back to the vacuum position to remove the steam, and finally back to the original position. After the operation, the hot dog sample was unloaded from the VSV chamber. The residence time at each position was independently controlled and adjusted. Three steam temperatures, 110, 123.9, and 137.8 °C, were used to treat the surface of hot dogs. The operating time for each operation in a cycle, including initial vacuum, steam, and final vacuum, varied from 0.1 to 2.0 s. For all experiments, the initial vacuum time was always set to be equal to the final vacuum time. At each steam temperature, hot dogs were treated in the VSV chamber using a combination of vacuum time and steam time (varying from 0.1 to 2 s). At least three independent surface temperature-time curves were measured and recorded for each combination of steam and vacuum time under a constant steam temperature.

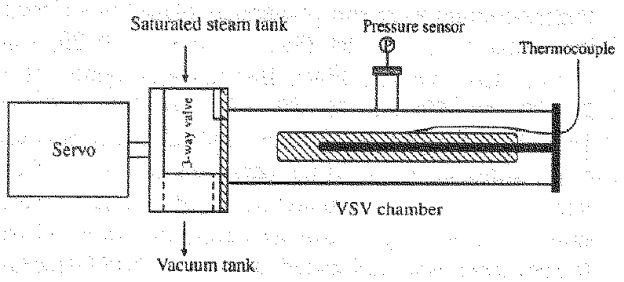

Fig. 1. Schematic diagram of modified VSV apparatus for treating hot dog samples.

2.9. Measurement of sample surface temperature and chamber pressure

To monitor and measure the surface temperature of a hot dog sample during VSV treatment, a thermocouple was carefully attached to the hot dog surface after it was mounted to the sample holder. Attachment of the thermocouple was accomplished by first applying a tiny drop (≈1 mm in diameter) of super glue (cyanoacrylate) on the surface of the hot dog sample, followed by lightly pressing the thermocouple tip against the super glue. The super glue was then carefully spread around the tip area of the thermocouple until it dried out. After that, the hot dog sample with the thermocouple was loaded into the VSV chamber. After the steam treatment, the thermocouple was separated from the hot dog by soaking in acetone for 15–30 min to dissolve the super glue.

The thermocouple attached to the sample surface was connected to the ADAC 5008TC data acquisition board. The voltage signal from the pressure sensor was wired to the PCI-DAS1200 A/D board. A data acquisition software LabTech Notebook (Version 10, Andover, MA) was used to simultaneously collect the temperature and pressure signals at a sampling rate of 200 Hz.

3. Results and discussion

3.1. Thermocouple response time

Fig. 2 shows the response of ultra-fine thermocouples to a step change in temperature. The average response time of the thermocouples, obtained from nonlinear regression of the experimental data according to Eq.

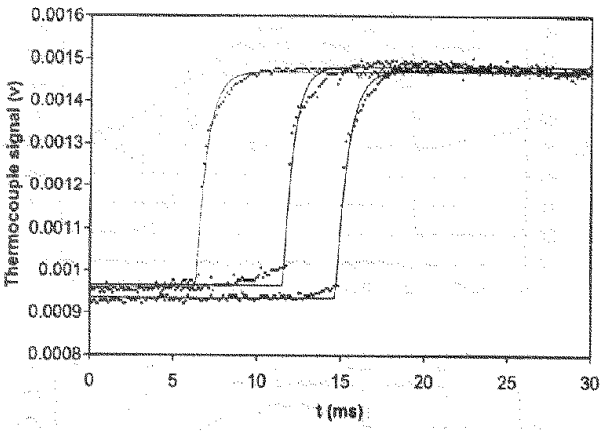

Fig. 2. Response of ultra-fine thermocouples to a step change in temperature. The smooth curves are the corresponding regression curves according to Eq. (2).

(2), was 0.675 ms with a standard deviation of 0.11 ms. The response time, according to the definition, is the time needed for a sensor to reach 63.2% of a step change. Longer time is needed for the sensor to develop to the full signal level after a step change. The sampling time is usually five times of the response time, or 5τ, of a sensor. Therefore the sampling time in this study was set as 5 ms, which was sufficient for the full signal levels to develop after a step change in temperatures. This sampling time was also adequate for the pressure sensor.

3.2. Surface temperature history

To prevent the loss of thermal energy through the wall of the stainless steel chamber, a band of electric heating elements was installed around the chamber. The function of the electric heating elements was to raise the temperature of the wall of the chamber to the temperature of the saturated steam. As the steam flushed into the chamber, no heat exchange occurred between the wall and the steam. An equilibrium in temperature was established immediately between the walls and the saturated steam. As a result, the thermal energy from the saturated steam would begin to transfer immediately to the food surface. Installation of the electric heating elements prevented the energy loss through the chamber wall. However, it presented a technical challenge for loading samples, since they were manually loaded to the chamber. Usually it took about 5–10 min to carefully load a sample. Since the chamber wall was hot, thermal radiation from the wall would cause the surface temperature of the sample to rise. Slight steam leakage into the chamber may have also contributed to the increase in the surface temperature. Therefore the initial surface temperature of the sample was higher than refrigerated temperatures usually found in the food industry. However, application of the initial vacuum would cause moisture in the sample to evaporate and thus lead to a drop in the surface temperature.

Figs. 3–5 are typical surface time–temperature curves of samples for three steam temperatures with various combinations of vacuum and steam treatment times. As a VSV process progressed, the pressure sensor responded immediately to pressure changes in the chamber and accurately registered the events of initial vacuum, steam, and final vacuum. The absolute pressure during each phase of treatment (initial, steam, and final vacuum) matched closely with the saturated steam/vapor pressures in the chamber. Clearly demonstrated in the figures, the sample surface temperature did not rise instantaneously to the temperature of the saturated steam even with an elevated initial surface temperature. Instead, the surface temperature of the sample began to rise exponentially after the steam was introduced. As time progressed, it gradually approached a plateau after

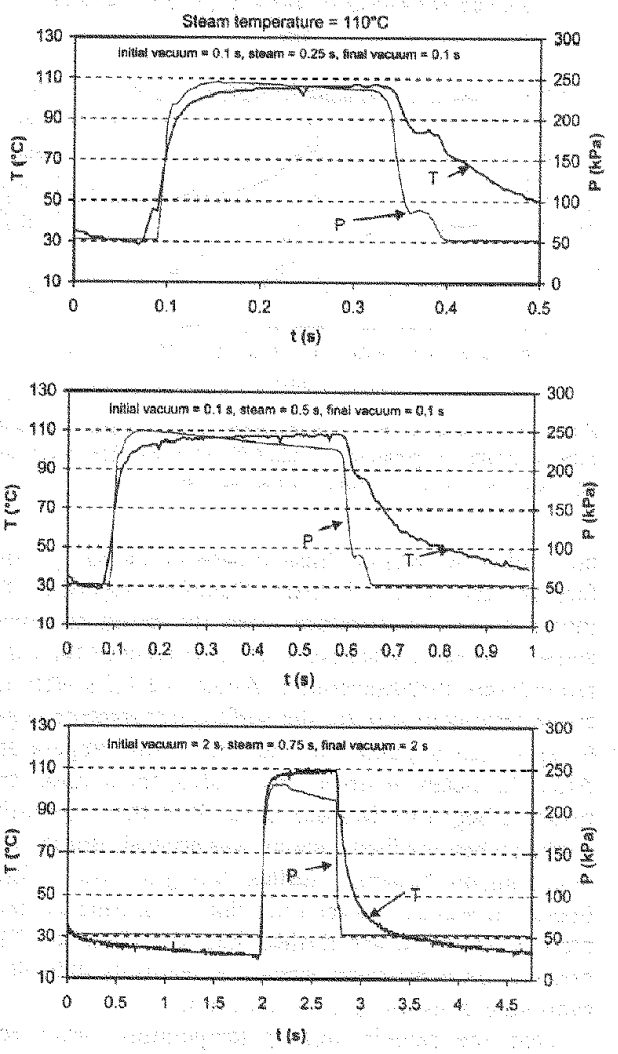

Fig. 3. Representative surface temperature curves of samples treated with a steam temperature of 110 °C (230 °F). The right axis represents the absolute pressure of the chamber.

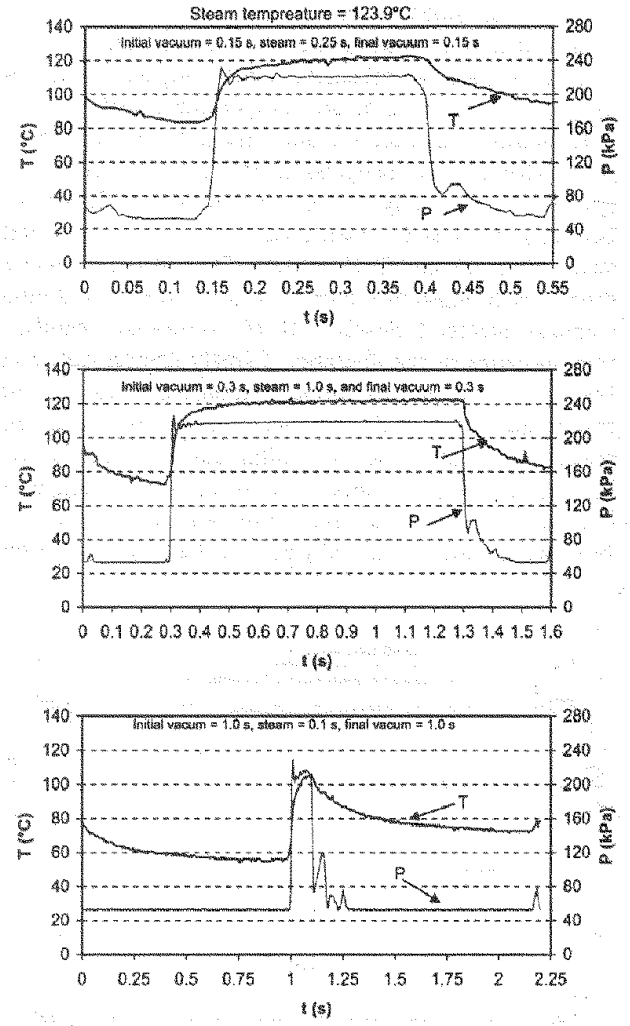

Fig. 4. Representative surface temperature curves of samples treated with a steam temperature of 123.9 °C (255 °F). The right axis represents the absolute pressure of the chamber.

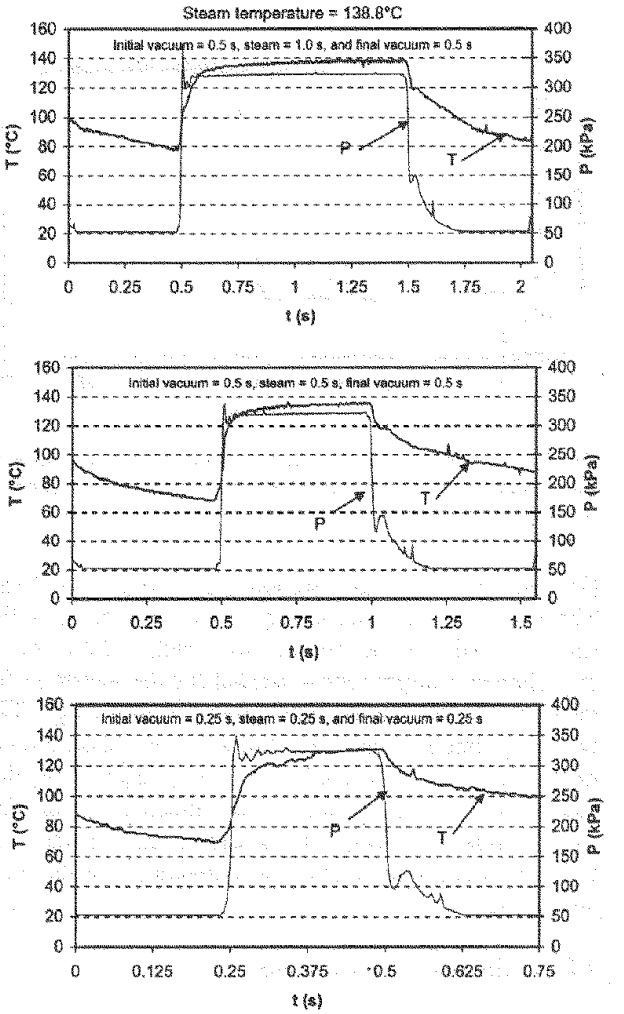

Fig. 5. Representative surface temperature curves of samples treated with a steam temperature of 137.8 °C (280 °F). The right axis represents the absolute pressure of the chamber.

an equilibrium was established between the sample surface and the saturated steam. Therefore, regardless the initial surface temperature when the steam treatment started, the surface temperature never reached the steam temperature instantaneously. About 0.2–0.3 s after the steam treatment started, the surface temperature began to approach a point close to the steam temperature. After the steam treatment was ended, the surface temperature began to decrease as result of the evaporative cooling when the final vacuum was applied. But the rate of cooling on the sample surface during the final vacuum operation seemed slower than that of heating immediately after the steam flushed into the chamber. This observation is expected, since it is relatively difficult to evaporate moisture from a solid food.

That the sample surface temperature never rose instantaneously to the steam temperature is explainable. When the saturated steam was introduced to the treatment chamber, an exchange of thermal energy between the sample surface and the saturated steam occurred immediately. When the steam was in contact with the sample surface, which was at a lower temperature, heat was transferred from the steam to the sample surface. The exchange of thermal energy between the sample surface and the saturated steam would cause the steam to condense, releasing the vast latent heat stored in the steam. The condensation of steam also formed a thin layer of condensate on the sample surface. Within the food sample, heat conduction occurred. The thermal energy was conducted to an interior layer immediately next to the top surface of the sample. This was a transient process of heat transfer until a steady state was established. In most applications of heat transfer involving steam condensation, the transient heat transfer phenomenon on the surface can be ignored, since the heating time is usually substantially longer. Since the steam time in a cycle of VSV is extremely short (0.026–0.4 s), the transient heat transfer phenomenon on the surface becomes significant. The sample surface

temperature cannot be assumed to reach the steam temperatures instantaneously. That the surface temperature of samples observed in this study never reached the steam temperature during the initial stage of steam process may have an implication to the real VSV processes. Because of the radiative heating effect from the chamber wall, the steam treatment started at a higher initial surface temperature, but it did not immediately rise to the steam temperature. Most foods treated in a real VSV process would usually start at a much lower initial temperature (<10 °C). Although the process used in this study was different from the real VSV process, it is natural to assume that a similarity exists between the two processes. The surface temperature of foods treated in real VSV processes reported in Kozempel et al. (2000b) may not have reached the steam temperature because of the short application times of steam (<0.4 s).

3.3. Mathematical modeling of surface temperature

To develop a mathematical model describing the process of VSV, it was assumed that the sample surface temperature was uniform when the steam treatment started, and the heat transfer occurred on the surface instantaneously after the steam flushed into the chamber. Heat was conducted from the surface into the interior of the sample. Because of the short steam time in each cycle, one could assume that heat conduction occurred within an extremely thin layer below the surface. Then the dynamic heat transfer within the thin shell can be expressed as

$$hA(T_s - T) = mC\frac{dT_{av}}{dt} \tag{3}$$

In Eq. (3), h is the convective heat transfer coefficient of a thin film of condensate surrounding the sample surface (W/m^2 °C), A is the sample surface area, T_s is the steam temperature (°C), T_{av} is the average temperature of the thin shell of the sample, m is the mass of the thin shell (kg), C is the specific heat capacity (J/kg °C), and t is the heating time. Since the steam time in VSV is very small and also the heat conduction occurs in a very thin shell, the average temperature, T_{av}, of the thin shell, can be used to approximate the surface temperature, T.

Replacing T_{av} with T and separating the variables in Eq. (3) yields

$$\frac{dT}{T_s - T} = \frac{hA}{mc}dt \tag{4}$$

Eq. (4) is an initial value problem with an initial condition: at $t = 0$, $T = T_i$, i.e., the sample surface temperature at the point when the steam is flushed into the chamber. Letting $k = hA/mc$, this equation can be easily solved, and the analytical solution is

$$T = T_s - (T_s - T_i)e^{-kt} \tag{5}$$

The coefficient k (s^{-1}) in Eq. (5) is a rate-limiting factor for the heat transfer between the steam and the hot dog surface. It is a function of the thermal property of solid foods (hot dogs) and the condensate film on top of the sample surface. As long as there is a temperature difference between the sample and the steam, a thin film of condensate always exists. One way to reduce the thickness of the condensate film is to maintain a constant flow of steam across of the sample surface to sweep way the condensate. Intermittent cooling should be avoided since cooling induces the formation of the condensate film on colder surfaces. If one could assume that the variation of the specific heat of hot dogs is relatively small, then based on the definition of Eq. (4), k should be independent of the initial surface temperature of the food treated in a VSV process, and the temperature of the steam. Since the VSV chamber is a closed system, and the saturated steam is a gas, the chamber geometry may not affect the condensate formation on the food surface; it may not affect k either. Therefore, this value potentially may be used in different VSV systems.

Eq. (5) can be used to analyze the temperature history on the sample surface during the steam treatment. In this study, nonlinear regression was used to correlate the experimental data with the mathematical model (Eq. (5)) and to determine the rate-limiting coefficient k. Fig. 6 shows three representative curves of the surface temperature history analyzed using Eq. (5). Because of a condensate film between the sample surface and the saturated steam, there would exist a temperature difference between the sample surface and the saturated steam. On average, the sample surface temperature was 2.95 °C below the steam temperature after an equilibrium was established between the steam and the sample surface.

Nonlinear regression was used to obtain the coefficient k in Eq. (5) from the experiments with steam time >0.5 s. There was a total of 35 curves with steam time >0.5 s. The average value for the coefficient k determined from all these 35 experimental curves was 30.5 s^{-1} with a standard error of 1.5 s^{-1}.

Since the coefficient k is theoretically a function of the physical properties of foods and the condensate film heat transfer coefficient between the food surface and the steam, Eq. (5) can be used to estimate the surface temperature history with different combinations of T_s and T_i. Fig. 7 shows the estimated surface temperature curves with different initial surface temperatures (0, 20, 40, and 60 °C) and under different steam temperatures (110, 123.9, and 137.8 °C). Although there is a wide range of initial surface temperatures, an equilibrium can be established between the steam and the surface around 0.2 s after the steam is flushed into the treatment chamber.

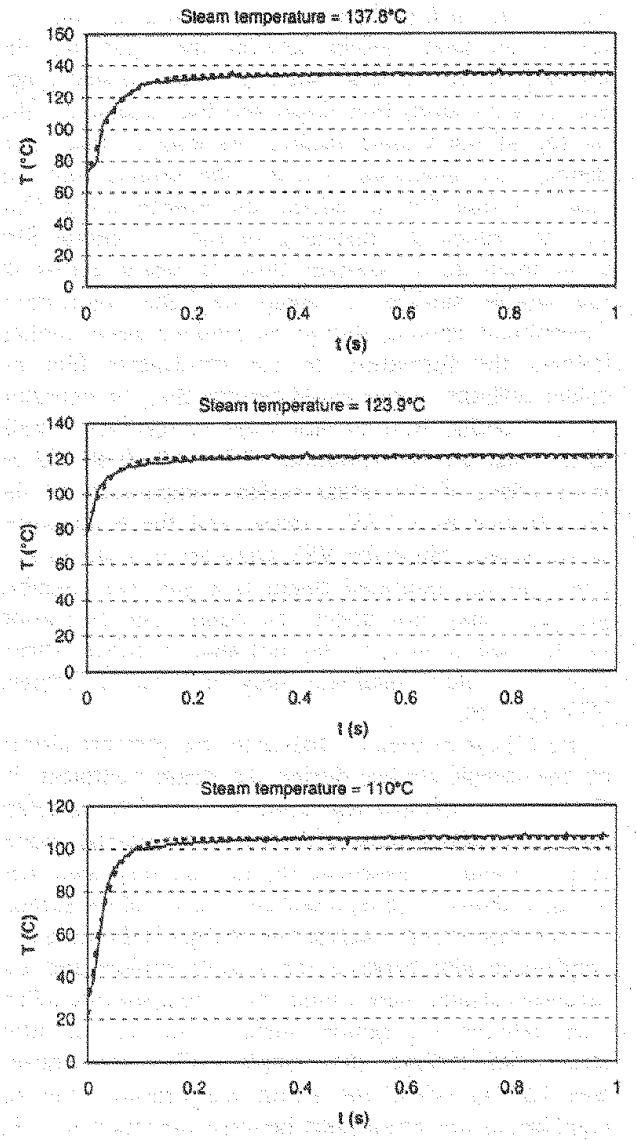

Fig. 6. Mathematical modeling of surface temperature of hot dogs during VSV treatment (Eq. (5)).

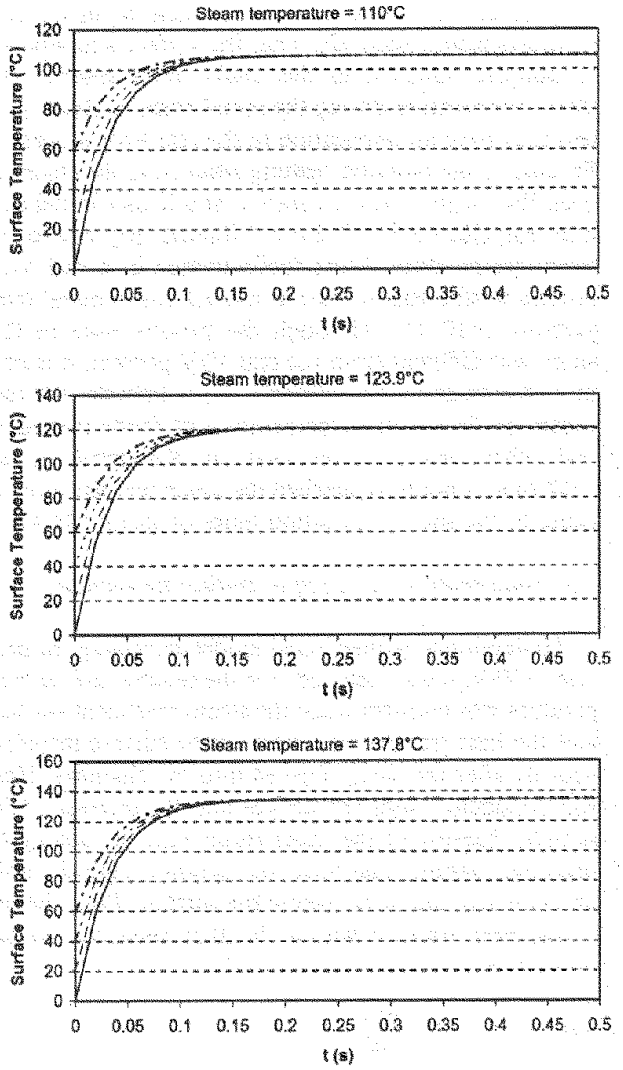

Fig. 7. Estimated surface temperatures at different initial surface temperatures (0, 20, 40, and 60 °C) and under different steam temperatures (110, 123.9, and 137.8 °C).

3.4. Estimation of lethality and explanation to bacterial survival during VSV

The destruction of microorganisms in foods under isothermal conditions generally follows the first-order kinetics, and the total lethality of a thermal process can be calculated using the general method (Eq. (6)). According to Murphy, Duncan, Johnson, David, and Smith (2002), the z value of *L. innocua* in beef patties was 8.67 °C. Using 70 °C as a reference temperature, the $D_{70\ ^\circ C}$ value of *L. innocua* was 13.58 s in beef patties. Since the F value calculated from Eq. (6) is equivalent to the total heating time under the reference temperature, the total log reduction can be calculated by dividing F with D_{ref}. Fig. 8 illustrates the estimated total lethality of *L. innocua* in beef patties as a function of the steam

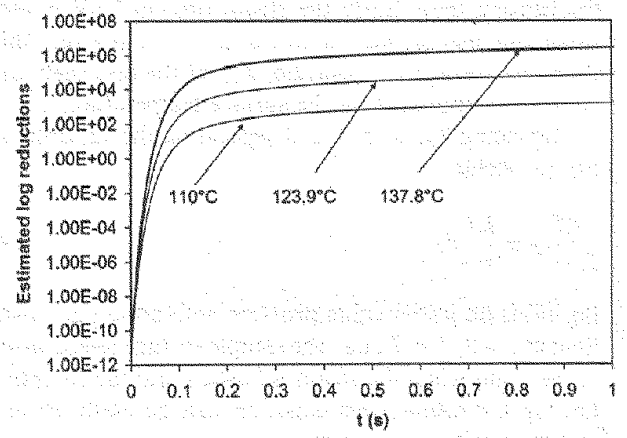

Fig. 8. Estimated total lethality as a function of steam time at three steam temperatures. Initial surface temperature = 0 °C.

time at three steam temperatures. The initial sample surface temperature for these curves was 0 °C.

$$F = \int_0^t 10^{\frac{T-T_{ref}}{z}} dt \quad (6)$$

According to the lethality calculation, bacterial kills of 7.9, 245, or 7635 logs of *L. innocua* in beef patties could be achieved after the first 0.1 s of steam treatment under the steam temperature of 110, 123.9, or 137.8 °C, respectively. After 0.3 s of steam treatment under 110, 123.9, or 137.8 °C, 308, 1.2×10^4, and 4.7×10^5 log-reductions could be achieved. If the D and z values of *L. innocua* in beef hot dogs was similar to those in beef patties, and if the surface of hot dogs were perfectly smooth, and if the all the bacteria were located on the surface only, then a 5-log reduction in bacterial count could have been achieved after 0.1 s of steam treatment at steam temperatures above 110 °C.

In almost all the published results concerning VSV, however, bacterial kills consistently ranged between 2 and 4 logs. One hypothesis to explain the survival of bacteria is that some of the bacteria may be distributed underneath of the sample surface and may not have been directly touched by the steam. Since the thermal conductivity of meat and poultry is usually very small, ranging from 0.3 to 0.6 W/m °C, heat conduction is a very slow process for solid foods. Since the steam treatment time in a VSV cycle is very short (0.026–0.4 s), there is not sufficient time to allow heat to penetrate deeper into the interior where bacteria may hide and to raise the temperature of these areas high enough to kill bacteria. Therefore, even though many cycles of VSV treatment have been used, bacteria hiding in these areas may have survived the heating.

3.5. Hypothesis of bacterial survival during VSV

One of the most common observations during VSV was that the foods emerging from the VSV chamber were always wet as if a layer of water was coated on the surface. The first natural explanation was condensation of steam to the sample surface after the final vacuum was applied. The decrease in the chamber pressure caused its temperature to drop. A layer of steam close to the sample surface may condense and form a film of water on the sample surface. This layer of condensate may become an insulation blanket (Fig. 9) between the surface of hot dogs and the incoming steam, impeding heat transfer in multiple, but brief cycles of vacuum and steam treatment.

On the other hand, hot dog surfaces are not smooth. There presents many pores on and below the surfaces. These pores are very small in size or even invisible to the naked eyes, but large enough to harbor bacteria. As long as there is any possibility that these pores may be filled with water (Fig. 9), steam cannot flow freely into these areas. The presence of water in the pores prevents the steam from directly hitting the bacteria hiding in the pores and thus may provide protection to the bacteria by insulating them from the steam in the chamber. Then heat must be transferred into these pores by conduction. There is no convection between the pores and the saturated steam in the VSV treatment chamber. Although the heat from the steam can be quickly convected to the hot dog surface, the conduction of heat from the surface to the interior of the hot dog is a much slower process. Heat conduction becomes the rate-limiting factor during VSV. As a result, a much longer steam time is needed.

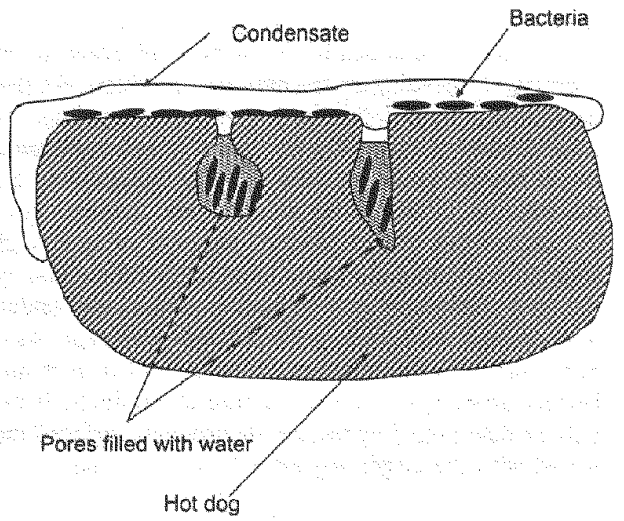

Fig. 9. Bacteria may hide in the pores filled with water.

The above hypothesis can be used to explain the experimental observations reported by Morgan et al. (1996b). In this study, multiple short VSV cycles (10, 20, 18, and 40) were used. Small chicken samples were treated with saturated steam at 126, 129, 130, 138, and 139 °C. The steam duration was 52, 103, and 124 ms. The most severe condition was 139 °C, 103 ms per cycle for 40 cycles. Only 3.0-log reduction was observed, and 3.6 logs of *L. innocua* survived after the VSV treatment.

The above hypothesis also can be used to explain why vacuum cannot improve the bacterial kill during VSV. Because the pores near the surface of untreated samples may be filled with water, vacuum is not effective to remove the water from the pores. Furthermore, it could induce the formation of a condensate layer on the hot surface, increasing the resistance of heat transfer.

4. Conclusions

The objective of the surface pasteurization of ready-to-eat meat/poultry products is to render these foods free of *L. monocytogenes* in the final packages. Therefore the steam surface pasteurization process must be de-

signed to eliminate *L. monocytogenes* potentially hiding in the pores underneath the surface of ready-to-eat products. Depending on the nature of products, the size, depth, number, and distribution of pores may differ. To render ready-to-eat meats free from *L. monocytogenes*, steam surface pasteurization must be designed to kill the bacteria hiding in the smallest and deepest pores. To achieve this goal, this study suggests using a single long steam treatment instead of multiple brief steam cycles. A final vacuum may be used to remove the residual heat on food surfaces to prevent thermal damage. As to how long a steam treatment time is needed, it is also heavily dependent upon the nature of products. It can only be determined by testing the products surface-inoculated with the target organism or its surrogates.

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